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RESEARCH

Technical screening of wind turbine installation vessel compatibility for offshore wind deployment in Brazil

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Abstract

This study evaluates the availability and technical suitability of wind turbine installation vessels (WTIVs) for offshore wind deployment in Brazil. With more than 80 GW in proposed capacity, Brazil faces an urgent need to assess whether large offshore turbines can be installed under conditions of limited infrastructure, regulatory uncertainty, and constrained vessel availability. Using a threshold-based screening procedure, the study evaluates 77 vessels against three core technical criteria: crane height, lifting capacity, and maximum operational depth. These thresholds reflect the installation demands of 15 MW turbines, the most frequently proposed configuration in Brazil's environmental licensing pipeline. Results show that only 22% of the evaluated vessels meet all minimum requirements, highlighting the country's reliance on a limited segment of the global fleet. The analysis is intentionally restricted to first-stage technical feasibility and does not yet incorporate broader contextual variables such as port infrastructure, permitting conditions, or financing constraints. Even so, the framework provides a transparent and replicable basis for aligning turbine-scale ambitions with installation capacity in Brazil. The approach may also support preliminary vessel-feasibility assessments in other emerging offshore wind markets facing similar logistical and infrastructural barriers.

Keywords Offshore wind power · Offshore wind turbine installation · Renewable energy · Offshore wind supply chain

1 Introduction

Over the past 50 years, human activity has accelerated greenhouse gas emissions, significantly impacting the world's oceans. Effects such as rising sea levels, ocean acidification, food insecurity, glacier melt, and altered hydrological cycles are becoming increasingly severe, necessitating immediate mitigation efforts (IPCC 2023).

Achieving a net zero-emission scenario will require tripling global renewable energy output by 2030 while doubling energy efficiency improvements (IRENA 2022). The urgency of emission reduction has spurred global adoption of renewable energy. In 2022, 77.6 GW of new wind power capacity were installed, increasing the global wind energy capacity to 906 GW, a 9% year-on-year growth. Estimates suggest that by 2024 annual global onshore wind power installations will surpass 100 GW, with projections reaching up to 136 GW per year by 2027 (GWEC 2023).

While these figures, include both onshore and offshore wind power, offshore wind remains underutilized despite the Earth's vast potential. Oceans cover 70.7% of the Earth's surface yet in 2022 offshore wind installations accounted for only 6.9% of the global wind capacity (IRENA 2022). Offshore wind is expected to grow rapidly, with new installations projected to increase at twice the rate of onshore wind (GWEC 2023). This trend offers significant opportunities, particularly for countries, such as Brazil, which exhibits favorable conditions for offshore wind development, including an extensive coastline, consistent trade winds, and large areas of shallow water where installations are less expensive and complex (Heptonstall et al. 2012).

Brazil's potential for offshore wind energy is bolstered by its established maritime infrastructure, which includes 33 ports (ANTAQ 2022) and a proven capacity to handle energy production in challenging marine environments. While wind energy has become a global reality, Brazil faces a

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delayed start in offshore wind power (OWP) development. A major hurdle is the absence of an approved legal framework, as the proposed bill "PL 11247/2018" remains unratified by Congress. Without clear regulations, Brazil risks falling behind as global offshore wind markets continue to expand.

Other countries have advanced to using floating and hybrid platforms for deep-water turbines. For instance, studies by Stansby and Li (2024) explored platform designs integrating wind and wave energy generation, while Faraggiana et al. (2024) analyzed innovative hybrid energy systems, combining different renewable sources to improve efficiency. Such advancements highlight the dynamic evolution of offshore renewable energy technologies, contrasting with Brazil's regulatory stagnation.

Globally, the offshore wind sector is rapidly scaling. In 2023, global wind energy installations surpassed the 1 TW threshold (GWEC 2023). However, this growth presents challenges, including supply chain constraints. Brazil's reliance on global vessel availability for Offshore Wind Farm (OWF) installations further complicates its development plans. At present, there is a substantial shortage of WTIVs, which are essential for the primary installation processes of offshore wind farms, including foundation laying and turbine installation. As of now, all suitable vessels are contracted through 2025, and the lead time for new vessel delivery is three to four years (H-BLIX 2022). This shortage is exacerbated by competition with other industries, such as oil and gas, for similar vessels.

Brazil faces additional challenges in meeting the planning requirements for its 96 offshore wind projects currently under review by IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources). These requirements include detailed schedules for vessel use—covering frequency, capacity, and routes—and alignment with national maritime spatial planning, none of which can be fulfilled until a specific vessel is selected for the project. The scarcity of WTIVs not only complicates logistical planning, but also inflates costs, potentially jeopardizing the financial viability of proposed projects.

Another critical factor is investment interest. The techno-economic characteristics of a wind farm, including site suitability and technology risks, account for 23% of its overall feasibility score (Solbrekke and Sorteberg 2024). For Brazil, the uncertainty surrounding regulatory approvals and vessel availability could result in significant cost overruns, rendering initial budgets insufficient. Effective planning is thus essential to address these challenges and pave the way for the development of offshore wind energy in Brazil.

Vessel scarcity significantly impacts projects and should not be overlooked in Brazil. Even countries with advanced frameworks face challenges: Orsted canceled its Ocean Wind 1 and 2 projects in the United States due to a vessel shortage causing multiyear delays (Shenk 2024). Similarly, the United Kingdom's SSE energy company reported delays for the 1.2 GW Dogger Bank A OWF due to poor weather, vessel unavailability, and supply chain issues (Twidale 2024). These examples highlight the need for Brazil to understand the offshore wind market and plan proactively.

The feasibility of offshore wind deployment in Brazil must be interpreted within a broader set of structural conditions that influence project viability. A preliminary PESTEL analysis—encompassing Political, Economic, Social, Technological, Environmental, and Legal factors—reveals key challenges and opportunities for the sector. Politically, Brazil has shown growing interest in offshore renewables through public consultations and planning documents, but federal-level regulatory implementation remains pending. Economically, the country holds significant industrial capacity and shipbuilding potential; however, port infrastructure remains underdeveloped for heavy-lift operations, and no domestic WTIVs are currently in operation. On the social front, public awareness of offshore wind is limited, although coastal states such as Ceará, Rio de Janeiro and Rio Grande do Sul have expressed support due to local employment potential. Technologically, Brazil has experience in offshore oil and gas, which provides a partial foundation for knowledge transfer—but lacks operational track records in floating offshore wind turbines (FOWTs) or grid integration at scale. Environmentally, the Brazilian coastline offers a vast technical potential, yet also includes sensitive ecosystems that require robust environmental licensing processes. Legally, the absence of a finalized regulatory framework for seabed leasing, maritime zoning, and offshore energy concessions remains a major barrier to project execution. These interdependent PESTEL elements highlight the urgency of coordinated regulatory action and infrastructure planning. At the same time, they reinforce the relevance of a technical screening approach: in a policy environment where key legal and environmental instruments are still under development, vessel compatibility remains one of the few objective and actionable decision-making dimensions available to stakeholders.

To address the lack of planning for WTIV allocation in Brazil, this study asks the following research question: what options do Brazilian offshore wind projects have for procuring vessels that satisfy their technical requirements? This question is important because Brazil combines a growing offshore wind pipeline with critical gaps in supply-chain readiness and regulatory development. The study, therefore, provides a context-specific assessment of vessel availability and procurement challenges, followed by a sensitivity analysis using a smaller reference turbine.

This study focuses on evaluating the technical compatibility of WTIVs for OWF deployment in Brazil. The analysis is based on measurable operational parameters—such as lifting capacity, crane height and operational depth—required for the installation of large turbines, particularly the 15 MW reference model. Broader design-related issues (e.g., foundation types, floating platforms, port infrastructure, and environmental licensing) are referenced to contextualize the vessel selection process, but are not quantitatively modeled. Factors, such as deck space, dynamic positioning capability, transport capacity, weather limits, and port compatibility, are, therefore, treated as second-stage decision variables rather than as first-stage screening criteria. Instead, these elements inform the framing of constraints and help interpret the implications of vessel suitability across different development scenarios. This scope ensures that the screening framework remains technically focused and adaptable, while remaining relevant to Brazil's regulatory and logistical offshore wind landscape.

While international studies have assessed the technical suitability and availability of WTIVs for offshore wind farm deployment, the Brazilian context remains insufficiently explored. In particular, limited attention has been given to the preliminary question of whether the currently available vessel pool is technically compatible with the turbine configurations proposed in Brazil's offshore wind pipeline. This study addresses that gap through a first-stage technical screening focused on measurable installation requirements. Although the present application is developed for Brazil, the screening logic may also support preliminary vessel-feasibility assessments in other emerging offshore wind markets facing similar logistical, infrastructural, or regulatory constraints.

This work is structured into eight sections. Section 2 provides a brief literature review on offshore wind turbine (OWT) installation, highlighting gaps specific to the Brazilian context. Section 3 outlines the technical, financial, and infrastructural background of Brazil's offshore wind sector, emphasizing key challenges related to WTIV availability. Section 4 details the methodological approach, including the definition of screening parameters, data mining procedures, and the threshold-based screening procedure adopted in this study. Section 5 presents the results, including vessel classification outcomes, sensitivity analysis for smaller turbines, and spatial implications. Section 6 discusses the methodological limitations, scope constraints, and potential future expansion of the framework. Section 7 draws the main conclusions and strategic implications for Brazil and other emerging offshore markets. Finally, Sect. 8 outlines directions for future research.

2 Brief literature review

The offshore wind literature has examined a wide range of topics, including turbine and foundation technologies, installation procedures, vessel operations, supply chain constraints, and broader planning challenges. However, these strands of research have often developed in parallel. Engineering-oriented studies tend to focus on installation mechanics and offshore operations, whereas planning-oriented studies typically emphasize resource potential, infrastructure, regulation, or deployment strategy. As a result, relatively limited attention has been given to the preliminary question of whether the available vessel fleet is technically compatible with the turbine configurations proposed in emerging offshore wind markets.

Several studies have contributed to the understanding of offshore wind installation from an engineering and operational perspective. Zhao et al. (2019) evaluated the feasibility of single-blade installation using floating crane vessels and highlighted the importance of vessel motion characteristics. Sarkar and Gudmestad (2013) proposed a method for monopile installation using preinstalled structures, while Jeong et al. (2016) investigated offshore lifting simulations under varying operating conditions. Acero et al. (2017) assessed allowable sea states during transition-piece installation onto monopile foundations. Taken together, these studies improve understanding of offshore lifting operations, installation procedures, and vessel-related technical constraints, but they are primarily oriented toward detailed engineering analysis rather than market-wide vessel screening.

Beyond engineering feasibility, offshore wind deployment is also shaped by logistics, supply chains, and vessel availability. Jiang (2021) reviewed OWT installation methods and vessel types, showing how installation strategies vary according to foundation concept, turbine size, and offshore conditions. Lantz (2021), in the context of offshore wind expansion in the United States, highlighted the importance of aligning deployment targets with vessel requirements, infrastructure readiness, and industrial capability. These contributions indicate that vessel availability is not merely an operational detail, but a planning constraint that can affect the timing, cost, and feasibility of offshore wind development.

Brazilian studies have so far focused mainly on offshore wind potential, regulation, and broader infrastructure conditions. Azevedo et al. (2020) assessed the offshore wind potential along the Brazilian coast and demonstrated the country's substantial technical resource base. Barboza Mariano et al. (2022) emphasized Brazil's regulatory and infrastructural gaps in comparison with other countries, while broader offshore wind reviews such as Díaz and Guedes Soares (2020) provide useful context on technologies and future sector trends. Even so, the specific issue of wind turbine installation vessel compatibility has remained largely unaddressed in the Brazilian case.

This gap is important because Brazil's offshore wind sector is advancing under conditions of regulatory uncertainty, limited port readiness for large components, and the absence of a domestic WTIV fleet. Existing studies help explain

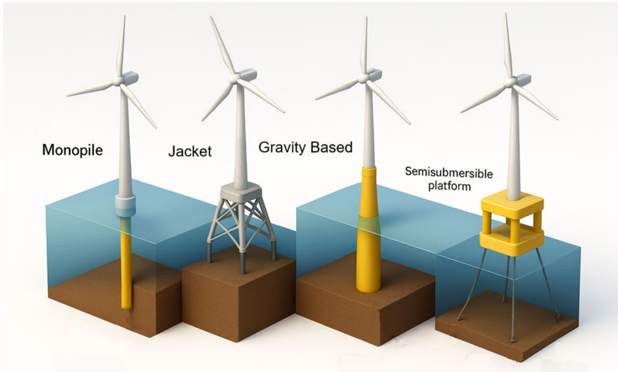


Fig. 1 Schematics of fixed-bottom foundations (monopile, jacket and gravity based) and semi-submersible floating foundation

the technical potential of offshore wind, the complexity of installation procedures, and the broader logistical challenges associated with sector expansion. However, a Brazil-oriented assessment of whether the currently available vessel pool is technically compatible with the turbine classes most frequently proposed in the national licensing pipeline remains insufficiently explored. The present study addresses that gap through a first-stage technical screening focused on measurable installation requirements.

3 Technical, financial and infrastructural background for Brazilian projects

The development of OWFs in Brazil requires addressing technical, financial, and infrastructural challenges specific to the region. Although Brazil benefits from an extensive coastline and offshore industrial experience, the sector still faces limited WTIV availability, the need for port upgrades, and high installation costs for large turbines. This section summarizes the main installation, cost, and infrastructure issues relevant to vessel feasibility.

3.1 Installation procedures

OWT installation involves distinct methods for fixed-bottom and floating foundations—Fig. 1 illustrates schematics of fixed bottom foundations and the semi-submersible foundations.

Monopiles are driven into the seabed using stabilizing grippers, while gravity-based foundations require seabed preparation to remove unsuitable materials up to 10 m thick (Ruiz de Temiño and Alonso 2013). Jacket foundations are more complex, involving pile installation frames for underwater positioning, requiring additional steps for secure placement. Floating turbines involve more intricate procedures. Spar foundations, displayed in Fig. 2 are towed to

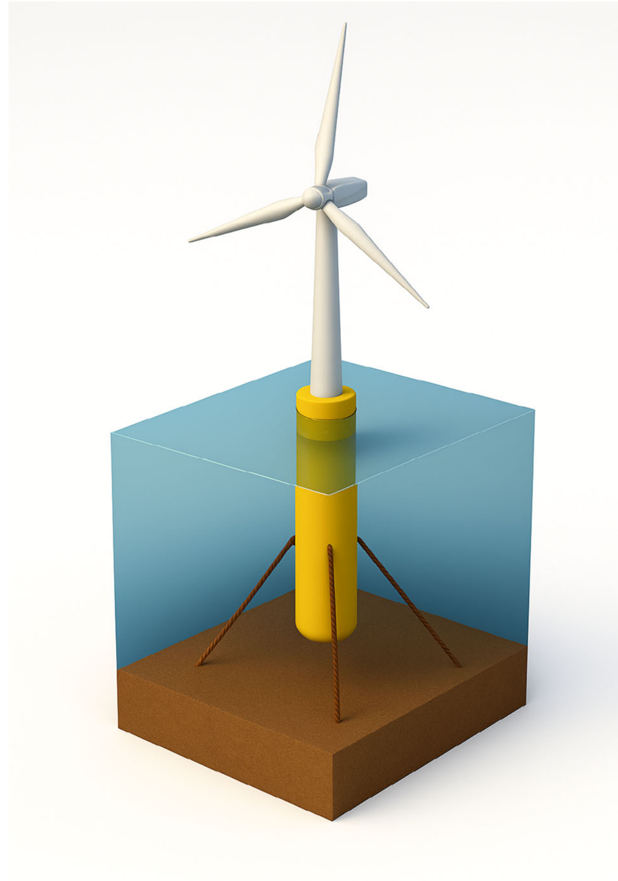


Fig. 2 Schematics of spar-buoy floating foundation

the site, ballasted, and assembled offshore before being connected to mooring systems. Despite their complexity, floating platforms have become essential for regions without shallow waters, leveraging existing maritime skills, such as tugging, anchoring, and ballasting.

Once foundations are secured, OWT components are transported to the site for turbine installation—key steps to a jacket and a spar platform installation are displayed in Fig. 3:

This process poses risks to timeframes, with offshore lifts prone to delays due to weather conditions. Pre-assembly onshore is preferred to reduce offshore lifting requirements. Six established methods for turbine installation range from transporting tower sections to connecting fully mounted turbines—component description, alternative method and number of lifts are represented in Fig. 4:

3.2 Financial factors

The financial feasibility of OWFs is heavily influenced by the costs of installation vessels, which depend on factors, such as OWF distance, to shore and turbine size. WTIV acquisition costs range from 335 to 375 million dollars when built in China, exceeding 700 million dollars for vessels, such as

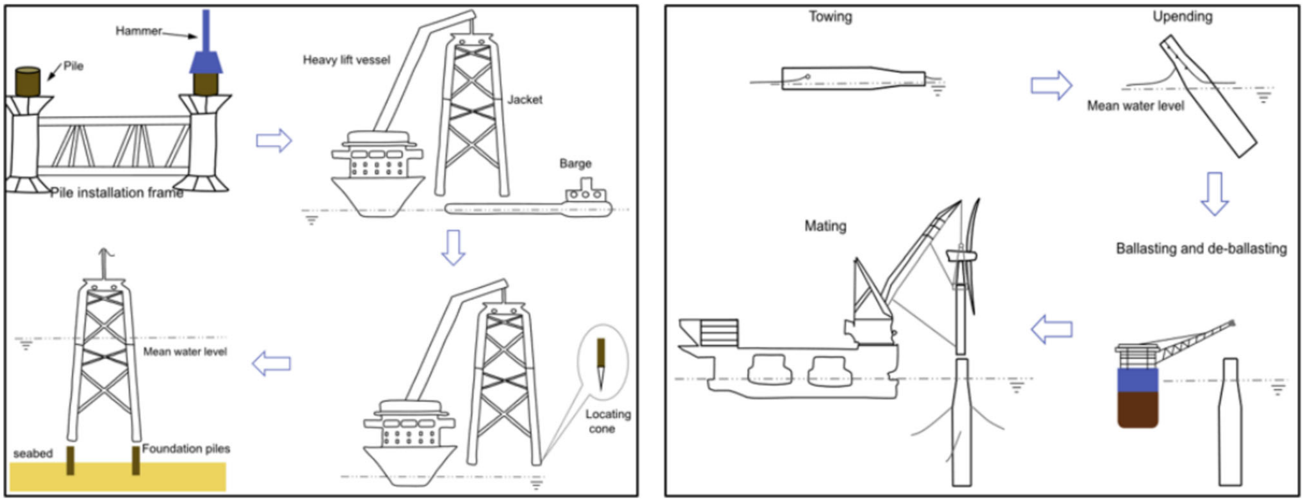


Fig. 3 Key steps of jacket foundation and spar platform installations (Jiang 2021)

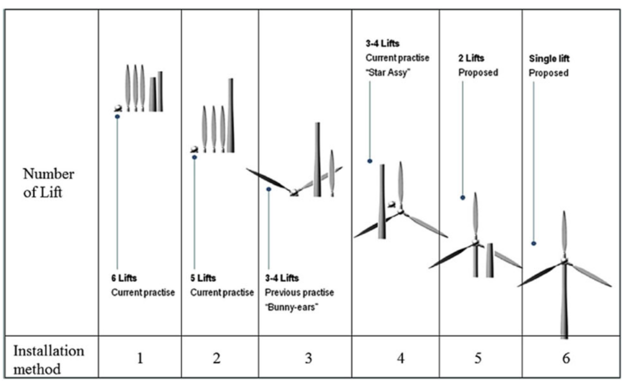


Fig. 4 Diagrammatic representation of installation methods (Ahn et al. 2017)

the WTIV Charybdis, built in the United States (Durakovic 2021; Cadeler 2024). Leasing such vessels costs around 30 million euros annually (Buljan 2022), while day rates vary depending on vessel type, as shown in Table 1.

Installation times also significantly impact costs. For fixed-foundation OWFs, installation times range from 1.33 to 14.83 days for foundations and 1.10 to 30 days for turbines (Lacal-Arántegui et al. 2018). For the largest turbines, total installation costs can exceed 11 million dollars per unit, where nearly one fifth of total capital expenditure (CAPEX) comes from transportation and installation (Ahn et al. 2017).

These costs require careful financial planning before an OWF project is initiated. Díaz and Guedes Soares (2020) estimated the CAPEX of the Ribadeo OWF in northern Spain at between 2727 and 4116 million euros for 88 turbines of 10 MW, depending on foundation type. They also estimated annual operating expenditure at 44.35 million euros. CAPEX and operating expenditure are only two of the indicators affecting project feasibility, but they already show the importance of planning when and where to invest in maritime transport and installation vessels to avoid cost escalation.

3.3 Technological advancements in offshore wind energy and their potential impact on vessel suitability

Recent advancements in OWTs include larger rotor diameters, higher tip heights, and improved power outputs. Since 2015, turbine sizes have increased from 192 to 300 m in height, and power output has tripled to 18 MW, with projections reaching 25 MW by 2030 (GWEC 2023). These advancements demand corresponding improvements in WTIV capabilities, as many vessels suitable for smaller turbines are inadequate for larger models—as illustrated by Fig. 5:

While innovations, such as lighter, more durable blades and integrated monitoring systems, reduce maintenance requirements (Bortolotti et al. 2023; Yang et al. 2022), these features have minimal impact on installation operations. Conversely, floating foundations have significantly expanded viable offshore areas, allowing installations in waters deeper than 60 m, where fixed foundations are impractical (Kempf et al. 2021).

One of the most relevant developments in offshore wind has been the advent of floating foundations, which expanded the range of viable offshore areas through installation and stabilization techniques suited to deeper waters. In such conditions, fixed-foundation installation becomes more expensive and complex.

Lifting OWTs requires vessel cranes capable of supporting the turbine's weight and reaching above the hub installation height. As turbines grow taller and heavier, only crane systems that evolve alongside these technical demands

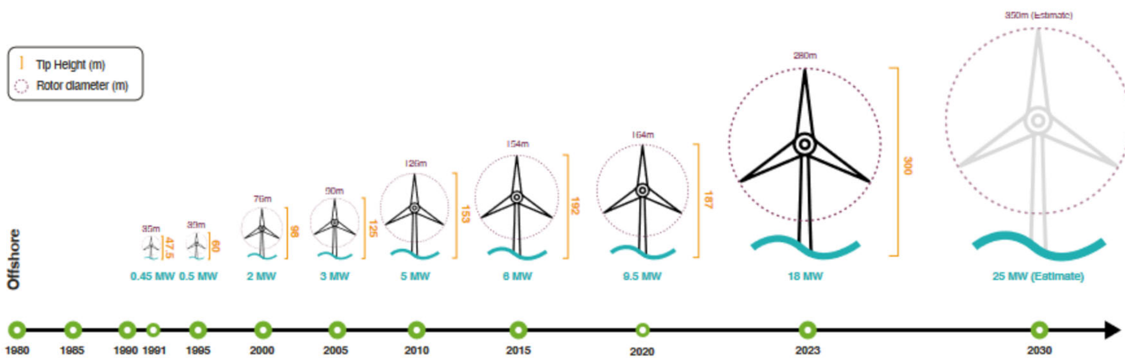


Fig. 5 Trend of offshore turbine size, 1980–2023 (adapted from GWEC (2023))

Table 1 OWT installation vessels and day rates (adapted from Jiang (2021))

Type	Specifications	2025 day rate (USD)
Tugboat	Diesel engines; large power-tonnage ratio (2.2–9.5)	1180–5900
Crane barge	Sheerleg or rotating crane; large crane capacity (1000–4000 tonnes)	94,400–118,000
Heavy lift cargo vessel	Loading and discharging of heavy objects; spacious main deck area	35,400–59,000
Jack-up barge	Non-self-propelled; medium to large crane capacity (200–1300 tonnes); dynamic positioning or mooring system;	118,000–212,400
Purpose-built jack-up vessel	Self-propelled; jacking system; dynamic positioning; large working deck; large crane capacity (800–1500 tonnes)	177,000–295,000
Semi-submersible crane vessel	Self-propelled; large lifting height and crane capacity (3000–20,000 tonnes)	330,400–590,000

Day rates were adjusted for 18% cumulative inflation since 2021. The inflation rate from 2021 to 2025 is an approximation based on U.S. Consumer Price Index (CPI) data published by the U.S. Bureau of Labor Statistics (BLS)

will remain adequate. Relying on the current fleet's capabilities—detailed later in this study—may pose significant challenges for future projects if not considered early in the planning process.

3.4 Brazilian ports and infrastructure

ABEEOLICA (2022) highlights that no Brazilian port is fully prepared for immediate OWF operations. Even so, new port construction is not necessarily required, since Brazil has a distributed coastline and existing infrastructure near potential project areas. Coastal shipping is more suitable than land transport for oversized components, and Brazil's offshore oil and gas experience may support future OWF logistics. However, specialized jack-up vessels for turbine assembly remain scarce and are largely committed to the global market.

4 Methodology

The methodological approach adopted in this study was designed to assess the technical feasibility of WTIVs in the context of Brazil's emerging offshore wind sector. It is structured to ensure transparency, replicability, and scalability, while remaining consistent with the current level of project and vessel data availability. The process is divided into four complementary steps: (i) compilation and refinement of the WTIV dataset; (ii) definition of turbine reference parameters based on licensing trends in Brazil; (iii) application of a threshold-based screening procedure across core operational criteria; and (iv) interpretation of vessel suitability under the technical conditions considered in this study. Each of these stages is detailed in the following subsections.

4.1 Definition of technical scope and screening parameters

This study examined vessels capable of lifting heavy equipment offshore and compared their technical specifications

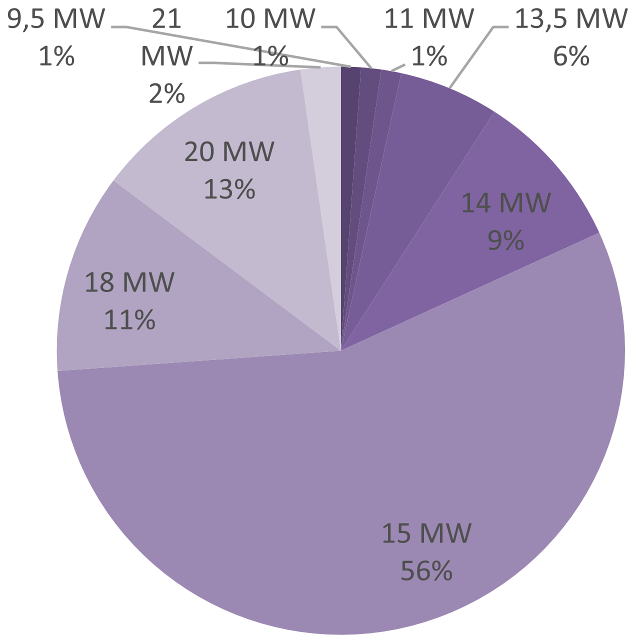


Fig. 6 Percentage of OWT power output selected for OWP projects in Brazil

Table 2 Key parameters of the IEA Wind 15-MW reference turbine

Parameter	Value
Power rating (MW)	15
Hub height (m)	150
Nacelle total weight (t)	820.88

with the most frequently selected turbine size in Brazilian offshore wind licensing requests, namely the 15 MW class. Of the 96 projects, 47 selected 15 MW turbines, accounting for a total of 8,899 units. The remaining projects chose turbine models ranging from 9.5 to 21 MW (IBAMA 2024), as shown in Fig. 6:

The 15 MW turbine with a monopile support structure, as defined by NREL (2020), served as the reference model for this study, with its key attributes detailed in Table 2.

Five vessel types commonly used in OWF installation—crane barges, heavy-lift vessels, jack-up barges, purpose-built jack-up vessels, and semi-submersible construction vessels—were included (Jiang 2021). Although WTIVs are purpose-built for such operations, many projects still use general-purpose vessels (IMCA 2022).

A survey of publicly available information from academic journals, industry reports, and market platforms identified vessels suitable for installing the reference turbine. A threshold-based screening procedure was then applied to identify vessels capable of meeting the nacelle-installation requirements of the reference turbine under Brazilian conditions.

4.2 Information source criteria for installation vessel applicability on Brazilian shores

Information about the global offshore wind market is provided by several specialized outlets, and compiling a report on Brazil's options for installation vessels, therefore, required data mining from publicly available digital sources. The detailed source-selection procedure is reported in the Supplementary Information. In the main text, only the decisions that affect reproducibility are retained.

Candidate sources were screened according to geographic coverage, technical coverage, publication age, website traffic, and organizational continuity. Following this screening process, Offshore Wind.biz (OWB) was selected as the primary source for vessel data, because it combined offshore-wind specialization with sufficient continuity and vessel-level technical disclosures for the purposes of this study.

4.3 Data mining analysis

Following source selection, the OWB vessel section was used to compile the dataset analyzed in this study. The 77 vessels listed within installation-relevant categories were initially considered suitable for screening, given that the selected source specializes in offshore wind and discloses technical characteristics for vessels involved in installation activities. For this study, the relevant specifications were maximum operational depth (MOD), maximum lifting capacity (MLC), crane height (CH), and leg height (LH), the latter for self-elevating vessels.

This research is limited to the capacity of a vessel to hoist the reference turbine nacelle of a determined weight to a determined height. Information regarding vessel dimensions, general cargo capacity, service speed, crane type, and deck area was not included in the present screening stage, although such variables may influence logistics and port selection in future work.

OWB discloses vessel data in limited detail, so some simplifying assumptions were necessary. Crane height was treated as the height from the water surface to the crane tip, and leg height was treated as the underwater extension of the legs for self-elevating vessels. Detailed variables, such as freeboard, draught, crane king height, and crane-specific structural characteristics, were not modeled. These simplifications are acceptable for first-stage technical screening, but not for detailed engineering verification.

4.4 Threshold-based screening model and scope limitations

To evaluate the technical suitability of WTIVs, this study adopts a threshold-based screening procedure. The objective is not to rank vessels by overall performance, but to determine whether they satisfy the minimum technical conditions required for nacelle installation under the reference turbine assumptions adopted in this study.

The screening incorporates three principal quantitative criteria: (i) maximum lifting height, (ii) maximum lifting capacity, and (iii) maximum operating depth. These parameters are treated as necessary conditions because the vessel must be able to lift the nacelle above the OWT tower top, support the full weight of the component, and operate within the relevant offshore depth range.

Each vessel in the database was evaluated against these three thresholds, defined by the reference turbine configuration. For each criterion, a binary score was assigned: score = 1 if the vessel satisfies the minimum required value, and score = 0 if it does not. Only vessels meeting all three threshold conditions were retained in the final suitable subset. No differential weights were applied to the criteria, and no ranking was performed among vessels that passed the screen. Accordingly, the present application should be interpreted as a technical admissibility filter rather than as a weighted multicriteria decision model.

The present framework is intentionally limited to first-stage technical feasibility. Broader contextual variables—-such as foundation type, floating platform compatibility, port readiness, weather limits, permitting conditions, and project-level financing constraints—were not incorporated into the current screening procedure. The rationale for this exclusion is that these factors remain highly relevant, but they are not yet supported by sufficiently standardized and project-complete data in the Brazilian offshore wind context. Their inclusion at this stage would require assumptions that could reduce the transparency and reproducibility of the analysis.

In this sense, the method focuses on measurable vessel characteristics that are immediately applicable to the technical problem addressed here. Future research may incorporate broader contextual variables through weighted, fuzzy, or other multicriteria decision-support approaches once regulatory conditions, project disclosures, and infrastructure data become more mature. The present study, therefore, aims to clarify a prior question: whether a technically compatible vessel pool exists at all for the turbine configurations currently proposed in Brazil.

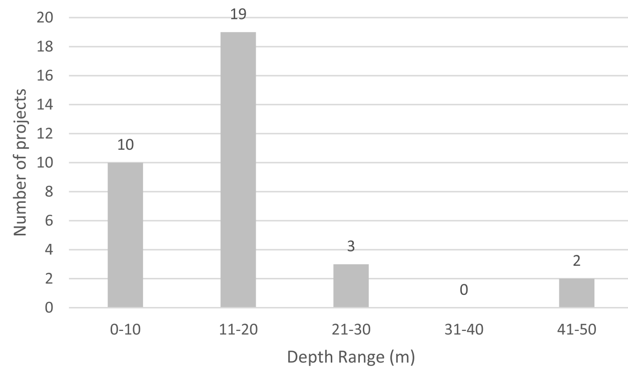


Fig. 7 Disclosed project water depth ranges for IBAMA licensing requests

5 Results

From the available material, 77 vessels were described by reference OWB as crane ships (CS), jack up vessels (JUV), offshore supply vessels (OSV), pipe layer vessels (PLV), semi-submersible vessels (SSV), and platforms. There were 20 OSVs, three platforms, and two PLVs, which are vessel classes commonly included in installation processes, but, in the present case, they cannot be directly involved in the transportation and hoisting of main OWT components due to lifting height and weight restrictions. The vessel classes fit were the SSV, CS, and JUV; considering only these, 55 vessels were included. Regarding the MLC, 36 vessels can handle the weight of a nacelle, regardless of the maximum height. The results are listed by weight range in Supplementary Table 2. With respect to the installation, 26 vessels are able to surpass a minimum height of 150 m (not considering the project water depth and MOD). Such vessels have their Preliminary hoisting height (PHH), the added value of CH and LH, displayed in Supplementary Table 3. The listed vessels, depending on the project depths, may be rendered unfit for installations due to a MOD below a specific project's depth—which, added to the tower height, may also reduce the number of able vessels. The specific installation depths reported by each project—where available—are shown in Fig. 7. These values are critical, as they may indicate whether a vessel is unsuitable for certain depth ranges.

Considering only the maximum weight hoisting capacity and PHH displayed in Supplementary Table 2 and Supplementary Table 3, 17 vessels are suitable for nacelle installation. The PHH is a value that disregards the water depths of individual projects and vessel MODs. This approach will be subsequently used to verify the vessel's ability to support a specific project's water depth.

One of the crane ships, Orion, and the semi-submersible vessel, SSCV Saipem 7000, have an unrestricted MOD-—these were considered suitable for all projects since both cranes reach heights above the minimum requirement. The

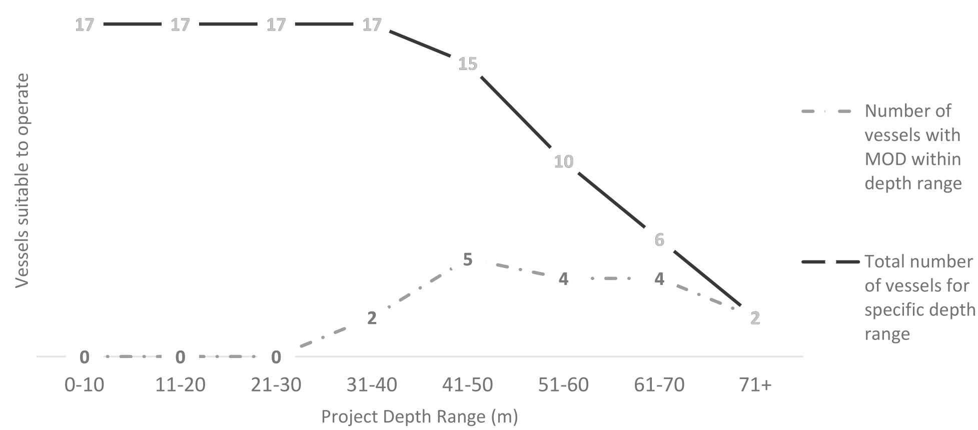


Fig. 8 Number of vessels per range and total vessels per range suitable per specific MOD

remaining 15 vessels are jack-ups with MODs of at least 40 m. Figure 8 shows vessels potentially apt to perform 15 MW nacelle installations per project depth.

The water depth at each project site is a key factor in determining the suitability of a vessel for nacelle installation. The aforementioned PHH serves as a reference for calculating a vessel's maximum installation depth (MID), which is the PHH subtracted by the reference tower height of 150 m. The MID will always result in a positive number, as shown in Table 3 below, and will indicate the vessel suitability for specific projects considering their specific depths.

The MID is always greater than the MOD, except in the cases of MPI Discovery and Aeolus. In these two cases, the MID will be their specific MOD. The total number of vessels per MID range is displayed in Fig. 9:

5.1 Sensitivity analysis

Following the 15 MW analysis, a sensitivity analysis was conducted to examine whether a smaller and lighter turbine would increase the number of technically suitable vessels. For this purpose, the same screening procedure was applied to the smallest turbine class identified in the IBAMA licensing requests, namely the 9.5 MW configuration. The results indicate a broader vessel pool than in the reference case. The reduced weight and lower hub height of the 9.5 MW turbine result in fewer operational constraints, allowing a larger number of vessels from the evaluated shortlist to meet the requirements. The selected reference values were a nacelle weight of 390 t and a hub height of 105 m for the MHI Vestas Offshore V164-9.5 MW turbine (Bauer 2021).

Results show that 10 additional vessels are able to lift 9.5 MW to its required height, and 15 are able to withstand its nacelle's weight. Considering only vessels that are able to satisfy both height and weight requirements, six additional vessels qualify, leading to an increase in the original number of 17 vessels able to install a 15 MW OWT to a total figure of 23 WTIV able to install a 9.5 MW OWT, as displayed in Fig. 10:

Interestingly, five out of the additional six vessels mentioned are OSVs—the original shortlist of 17 WTIV apt for the 15 MW OWT included only one vessel from this category, the 'Normand Maximus'. These additional five vessels bring the percentage of OSVs suited for the 9.5 MW OWT up to over 25%. The details for these additional vessels are displayed in Supplementary Table 4.

Specifically, this broader applicability enhances project flexibility, offering developers more options for vessel selection and potentially reducing logistical and financial bottlenecks. By utilizing these additional vessels, project timelines and costs could be better optimized, as the dependency on state-of-the-art WTIVs becomes less critical for projects featuring smaller turbines. This finding emphasizes the importance of aligning turbine specifications with available maritime infrastructure to streamline OWF development, particularly in emerging markets such as Brazil. Future studies should explore the dynamic interplay between evolving turbine designs and vessel suitability, as well as the implications for local supply chain readiness.

6 Final remarks

This study highlights the significant challenges Brazil faces in developing its OWF industry, particularly the scarcity of specialized vessels for turbine installation. Although Brazil's maritime infrastructure is generally capable, the lack of WTIVs remains a critical obstacle. Based on vessel data and IBAMA project licenses, 17 vessels were identified as potentially suitable for installing 15 MW turbines, the most common size planned for Brazilian OWFs. However, only a few vessels are prepared for larger turbines, such as 20 MW models, posing further challenges for scaling up the industry.

The study has several limitations. It relies on hypothetical scenarios and publicly available data, which may not

Table 3 Vessel crane and leg extensions, ship class, and reference lengths for hoisting a nacelle

Vessel name	Max water depth	Crane height	Leg height	Vessel category	Preliminary hoisting height	Maximum installation depth
Seajacks Zaratan	55	92	65	Jack-up	157	7
MPI Enterprise	45	102	70	Jack-up	172	22
Orion	Unrestricted	175	0	Crane ship	175	25
Friedrich Ernestine	45	102	73	Jack-up	175	25
Wind Orca	60	97	80	Jack-up	177	27
JB-117	45	98	80	Jack-up platform	178	28
JB-118	45	98	80	Jack-up platform	178	28
Blue Tern	65	96	88	Jack-up	184	34
Innovation	65	108	78	Jack-up	186	36
Sea Installer	55	115	73.5	Jack-up	188.5	39
MPI Adventure	40	120	70	Crane ship	190	40
Sea Challenger	55	115	76	Jack-up	191	41
MPI Discovery	40	120	73.5	Jack-up	193.5	44
Seajacks Scylla	65	105	95	Jack-up	200	50
Wind Osprey	70	132	80	Jack-up	212	62
Aeolus	45	130	87	Jack-up	217	67
SSCV Saipem 7000	Unrestricted	198	28	Semi-submersible	226	76

Fig. 9 Number of total vessels per MID range

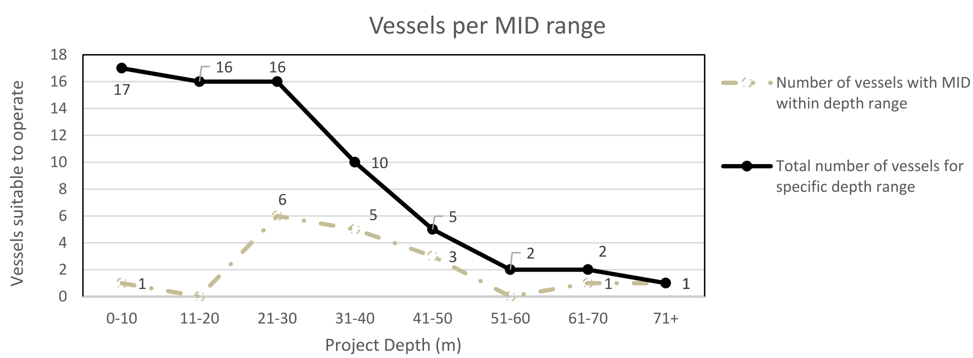
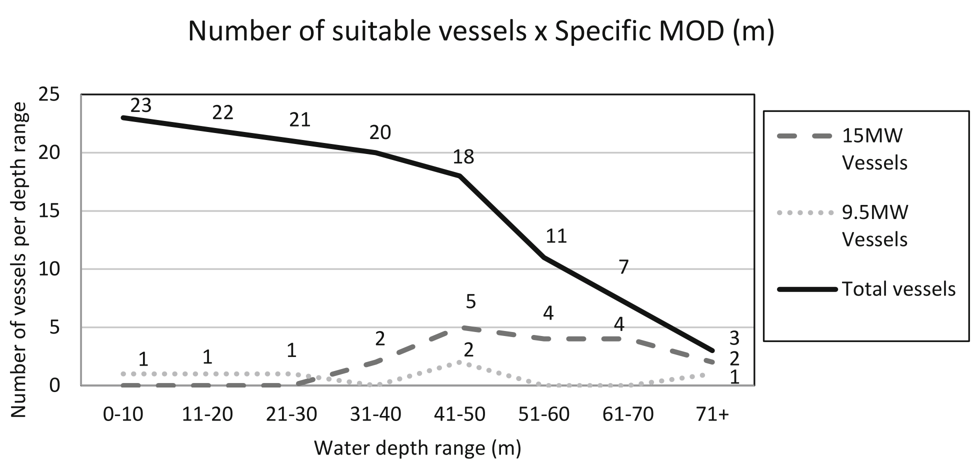


Fig. 10 Number of vessels suitable for 15 MW turbine installation, additional vessels suitable for 9.5 MW turbine installation, and total vessels by maximum operating depth range



fully reflect evolving market dynamics. Future planning must account for varying turbine specifications required by different local maritime conditions, including size, weight, and installation demands. Financial and regulatory uncertainties, such as tax policies, vessel procurement costs, and the lack of a finalized legal framework, also impact feasibility assessments.

Additionally, incomplete technical specifications from prospective projects introduce uncertainty. Factors, such as water depth, turbine models, and vessel capabilities, remain unclear. Broader knowledge of vessel attributes, including deck area, draught, and freeboard, is needed to assess their suitability for Brazilian port operations.

Future studies should incorporate lifecycle analyses of vessels to estimate decommissioning timelines and integrate finalized turbine details for more accurate predictions. Including specifications for foundations, blades, transition pieces, and cables—which require different vessels and installation methods—will provide a comprehensive understanding of Brazil's OWF requirements.

Despite its limitations, this study underscores the critical vessel scarcity for nacelle installation in Brazil and highlights the need for detailed technical and logistical planning to support future OWF projects.

The restricted shortlist of suitable WTIVs observed in this study is not an isolated technical outcome—it is deeply shaped by Brazil's current offshore wind readiness, as revealed by the PESTEL framework. The absence of national vessel standards, limited port draft and crane capacity, and undefined seabed concession mechanisms all reinforce the urgency of using clear-cut technical criteria to guide immediate project planning. The results underscore that, in Brazil's nascent regulatory and logistical environment, the technical feasibility of deploying 15 MW turbines is already a major constraint, even before financial or legal risks are accounted for. This validates the use of a simplified, but rigorous vessel selection model as an effective planning tool in early-stage offshore wind markets.

6.1 Limitations and outlook for future integration of contextual constraints

The results of the vessel screening reveal a critical constraint in WTIV availability for 15 MW turbine installation along the Brazilian coast. While this analysis was intentionally limited to verifiable technical parameters, it is important to acknowledge that other contextual factors—such as foundation design, floating platform requirements, regulatory approval processes, and cost feasibility—will play an increasingly central role in offshore wind logistics as the sector develops. At present, however, Brazil's offshore wind market lacks both regulatory maturity and operational precedent in these areas. There are no deployed FOWTs, no defined vessel certification standards for deep-sea operations, and no cost benchmarks that could meaningfully inform a vessel selection process.

Therefore, the exclusion of these variables in this study does not constitute an oversight, but reflects a necessary constraint: their inclusion, at this stage, would add speculative layers to an already narrow shortlist and potentially obscure rather than clarify the key technical bottleneck. As regulatory clarity emerges and project-level data accumulates, future assessments should incorporate these additional decision layers. For now, the present study demonstrates that even under strictly technical criteria, Brazil faces significant logistical barriers to scaling offshore wind infrastructure.

7 Conclusions

The results show that 17 vessels are technically suitable for 15 MW turbine installation, while the number rises to 23 when a smaller 9.5 MW turbine is considered. Five of the six additional vessels identified in the sensitivity analysis are offshore support vessels, whereas only one vessel in the 15 MW-compatible subset belongs to this category. This result suggests that the vessel category best suited to offshore wind installation may vary with turbine size.

This variation emphasizes the importance of flexible project planning that incorporates the evolving technological and logistical landscape. Furthermore, the study sheds light on the necessity for regulatory clarity and robust financial strategies to overcome market uncertainties and supply chain limitations.

The results presented in this paper provide a foundation for informed decision-making in Brazil's nascent offshore wind sector. By identifying critical gaps and proposing directions for future research, this study contributes to the broader discourse on sustainable energy development. Addressing the challenges highlighted herein will be pivotal for Brazil to harness its offshore wind potential effectively, paving the way for a cleaner and more resilient energy future.

8 Recommendations

The analysis presented in this study should be updated as new information becomes available from OWF projects, particularly details, such as water depth and turbine models. As nearly two-thirds of the projects lack water depth data and some disclose conflicting information, systematic updates are essential to understand nacelle installation challenges. Quarterly updates following Brazilian government auctions for OWF areas would refine the analysis, especially given project distances from the coastline (10–90 km) and installation depths (5–120 m), which significantly affect vessel suitability and installation methods. Future studies should also explore how environmental factors, such as extreme weather and seasonal variability, impact installation timelines and vessel requirements.

Advancements in turbine technology, such as the custom specifications of the Vestas V236, should be incorporated into future analyses to account for changes in nacelle heights and weights. Detailed vessel data, including crane specifications and operational limits, will further enhance vessel suitability assessments.

Investments in vessels capable of supporting larger turbines (e.g., 20 MW) are critical for keeping pace with industry advancements. Stakeholders must prioritize vessels with high hoisting capacities and suitable configurations while planning for logistical efficiencies through proximity to ports and coastal shipping (cabotage).

Policy makers should address regulatory gaps and supply chain constraints to support the industry's growth. Establishing adaptive legal frameworks and incentivizing investments in shipyards and new vessels will boost confidence and modernize the sector. Collaboration between developers and policy makers should focus on port infrastructure improvements and industry preparedness for non-specialized OWF vessels.

Future work should examine the role of onshore and offshore advancements, such as multi-rotor and bladeless turbines, and revisit findings as the industry evolves. It is also necessary to evaluate the compatibility of identified vessels with other OWF phases, including foundation installation, cable laying, maintenance and decommissioning.

A structured update framework is essential, including quarterly data reviews, continuous integration of new technological and project information, and adjustments to reflect vessel capabilities, turbine advancements, and project needs. This will ensure that the study remains relevant and aligned with the dynamic offshore wind industry.

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Data availability Data is provided within the manuscript and supplementary information files.

Declarations

Conflict of interest The authors declare no financial or non-financial competing interests.

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